DESCRIPTION

The invention relates to a method, an apparatus and a
software product for creating a three-dimensional model
5   for a tangible existing object, in particular for
creating a surface model or solid model or an FE model
(FE: Finite Element) from digitized data of the object.

In several technical fields there is a strong demand for
10 converting the image of a tangible existing object into a
computer model as real as possible. While simple objects
can mostly be reconstructed quite well by means of CAD
programs (CAD: Computer Aided Design), FE programs or the
like, this is increasingly difficult in case of complex
15 structures.

The discrepancy between demand and what is really
possible is particularly evident in biotechnology, for
instance, when the highly complex shape of anatomical
20 structures is to be modeled. The geometrical or
morphological inaccuracies of the model come in to bear
especially when, based on the model, an FE analysis is to
be carried out for calculating the physical behavior of
the object.
25

In case of creating an FE model consisting of nodes and
elements, there are in principle two different methods of
creating the FE model, i.e. a direct and an indirect
method. In the direct method, fixed nodes are provided to
30 the FE program, and in the indirect method it is the FE
program which selects the nodes from given geometrical
elements (e.g. surface models or solid models, lines or
points).

35 Upon studying the FE models which have been generated in

biotechnology so far, it will be noted that most of the proposed methods are direct methods in which fixed nodes are provided to the FE program.

5   Fig. 13 shows an example of a directly constructed FE model of facial soft tissue as disclosed by Motoyoshi M. et al. in "Finite element model of facial soft tissue. Effects of thickness and stiffness on changes following simulation of orthognathic surgery.", *J Nihon Univ Sch*

10   *Dent* 35, 118-123 (1993). This method does without a morphologically exact conversion of the object structure into the virtual space and makes the attempt to reproduce the complexity of the structure as well as possible by manual reconstruction.

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FE models may also be created by linking layers. In this case the geometrical data of the object is obtained by tomographic methods or preparing histologic sections.

20   For carrying out a point-based linking of layers, the tomograms obtained are digitized and the borders of the structure in question are identified. Then, nodes are defined on the boundaries of each layer to be first linked two-dimensionally in the respective layer and then

25   three-dimensionally between the individual layers. Fig. 14 shows an FE model of a tooth obtained by such a point-based linking of layers, as disclosed by Lin C. et al. in "Automatic finite element mesh generation for maxillary second premolar.", *Comput Methods Programs*

30   *Biomed* 59, 187-195 (1994).

The linking of layers may also be carried out on the basis of voxels. For this purpose a defined square grid is laid over each tomogram obtained and a cubic element

35   is assigned to each square corresponding to a voxel in

the layer. Each element in a lower layer, which is not
covered to a certain extend by the structure in question,
is omitted. The remainder are layers made of uniform
elements which, as piled up, constitute a three-
5 dimensional FE model made of cubic elements. Fig. 15
shows such an FE model of the human skull obtained by a
voxel-based linking of layers, as disclosed by Camacho D.
et al. in "An improved method for finite element mesh
generation of geometrically complex structures with
10 application to the skullbase.", *J Biomech* 30, 1067-1070
(1997).

A somewhat different approach was chosen by van Zyl P. et
al. in "Three-Dimensional finite element of a human
15 mandible incorporating six osseointegrated implants for
stress analysis of mandibular cantilever prostheses.",
Int J Oral Maxillofac Implants 10, 51-57 (1992). An FE
model of a lower jaw as shown in Fig. 16 was created by
three-dimensionally linking a point cloud obtained from
20 reflection-type micrographs. The point cloud was directly
input into an FE program, with the points of the point
cloud being used as nodes for the FE model. The automatic
linking of the nodes, however, is not particularly
reliable. Common FE programs frequently have difficulties
25 in linking point clouds with different densities, so that
usually special programs have to be used for three-
dimensionally linking a point cloud. As these programs
are not compatible with standard FE programs, the results
are isolated solutions on the software side, which can
30 only be handled by a skilled person.

Indirect methods for creating an FE model have been
successful mainly in engineering. In the indirect
methods, user-defined geometrical elements are provided
35 to the FE program for automatically calculating the

position of the nodes, wherein the geometrical elements
define only the periphery and boundary of the FE model
further on. The geometrical elements are either generated
in the FE program or imported as surface models or solid
5 models through so-called CAD-FEM coupling from a CAD
program.

For creating the FE model indirectly, there are two
alternative methods of generating the coordinates of the
10 nodes: In case of so-called "mapped meshing", nodes are
determined to form quandrangular elements or hexahedrons.
In case of "free meshing", triangular elements or
tetrahedrons having intermediate nodes (so-called
parabolic elements) are formed which fit particularly
15 well with complex geometries.

What matters is that, in the indirect method, it is
usually necessary to manually construct the geometrical
elements to be provided to the FE program in the FE
20 program or in a CAD program. In engineering, this is not
a disadvantage because most products are designed by
means of a CAD program. In biotechnology, however, the
indirect method has not been successful with a few
exceptions such as in the evaluation of artificial
25 structured parts such as hip prostheses and the like. The
inaccuracies that occur when a tangible object is
reproduced by direct construction are simply too large.

Up to date the only solution for converting the image of
30 a tangible existing object into a format available to
CAD-FEM coupling is reverse engineering. In reverse
engineering, the object is digitized and CAD surfaces are
created by surface reconstruction, which may be imported
into an FE program. The CAD surfaces are usually
35 comprised of freeform Bézier or NURBS patches (NURBS:

non-uniform rational B-spline surface) which are fit
piece by piece by means of a net of control nodes to the
surface shape of the object. NURBS patches are usually at
least bicubic parametric surface elements each of which
5 approximates the object surface with two polynomial
curves of third order. Solving the set of linear
equations causes the more trouble the higher the order of
the polynomials is, but achieves a more exact fit of the
surface elements to the surface shape of the object. Due
10 to the complicated algorithm used for surface
reconstruction, reverse engineering software has been
very expensive so far. Moreover, the calculations are
highly time-consuming.

15 Besides, it was found that the fit of Bézier or NURBS
patches to the surface shape of a geometrically complex
structure is often inaccurate and that frequently
irregular CAD surfaces are generated which can not be
processed with CAD programs or FE programs.
20
The object of the invention is to provide a method, an
apparatus and a software product which are capable of
creating an accurate three-dimensional model of a
tangible existing object with relatively low computing
25 effort.

The above object is achieved by a method according to
claim 1, an apparatus according to claim 6 and a software
product according to claim 9.
30
The invention is characterized by first digitizing the
object in question to create a mesh model of the object,
then breaking the mesh model into bilinear surface
elements and finally uniting the bilinear surface
35 elements to a surface model or solid model.

By the term "mesh model", polyface meshes, surface meshes
or polygon meshes are understood, which are typically
comprised of a finite number of polygons, wherein two
5   vertices or nodes define one edge at a time and a
plurality of such edges describes a geometrical body. The
geometrical description of the body is effected in the
mesh model in a purely numerical way. That is, in
contrast to an analytic approach the geometric shape is
10   not defined by mathematical equations, but purely by the
location and density of the vertices or nodes.

With such meshes being described in a purely numerical
way, the meshes can be created by digitizing the object.
15   Digitizing may be carried out in different ways. For
example, the object may be scanned optically or by
contact to create a point cloud describing the object
surface. This point cloud is used for generating the
nodes for the mesh representation. Alternatively, surface
20   images or tomograms are made of the object to be
digitized. Using these images, the boundaries of the
object are identified and individual points of the
boundaries are used as nodes for the mesh representation.

25   Up to now it has been acted on the assumption that the
numerical data of such mesh models cannot be used offhand
for creating a surface model or solid model described by
analytic functions. For example, a warning can be found
in the German instruction manual of AutoCAD 2000™, page
30   719 according to which CAD programs can convert solids
into surface meshes, but not surface meshes into solids.
For converting the numerical data into analytic data, it
was necessary so far to take the troublesome line of
reverse engineering which is not always successful, in
35   particular when dealing with complex geometries.

The invention bridges the numerical and the analytic
description of object data by breaking the numerical data
of the mesh model into the analytic data of bilinear
5 surface elements.

By the term "bilinear surface element", a surface patch
defined by two polynomial curves of first order or two
straight lines is understood. The end points of the
10 straight lines are given by the nodes of the mesh. The
two straight lines of each surface element form two edges
of a polygon course, with the other edge being obtained
by connecting the end points of the straight lines. Each
surface element has its own edges which are not shared
15 with the adjacent surface elements.

The bilinear surface elements are preferably triangular,
because triangular surfaces can be fitted particularly
well to complex geometries. In such a triangular surface,
20 one of the end points of one straight line of the surface
element coincides with one end point of the other
straight line, with the third edge of the triangle being
formed by the other end points. Alternatively, the
bilinear surface element may have a shape with four edges
25 (e.g. a square), so that the end points of the straight
lines do not coincide.

If the bilinear surface elements are to be processed in a
CAD program, the bilinear surface elements are preferably
30 in the shape of NURBS patches because NURBS patches are
invariant against rotation, scale, translation and
projection. It should be noted that the option of
freeforming NURBS patches of higher degree is abandoned,
because the surface elements used are bilinear.

35

For converting the mesh model into bilinear NURBS patches, the mesh is preferably converted into the IGES format (IGES: Initial Graphics Exchange Specification). The IGES format is an ANSI standard defining a neutral

5 format for data exchange between different CAD, CAM (CAM: Computer Aided Manufacturing) and computer visualizing systems. In this case, the bilinear surface elements conform to IGES #128 entities provided for rational B-spline surfaces.

10

After breaking the mesh into individual bilinear surface elements, the bilinear surface elements are united to create a closed surface model or a closed solid. For this purpose the opposing edges of two adjacent surface

15 elements are stitched together. In other words, the previously separate edges of the surface elements are combined to a common edge, so that one surface element merges with the other surface element. Since all the surface elements are plane, the surface elements do not

20 merge continuously but form a facetted surface composite.

The above-mentioned facetted surface composite constitutes a surface model of the digitized object. If the surface composite surrounds a finite volume quasi

25 leak-proof, a solid model of the digitized object is formed.

The surface model or solid model can easily be imported into an FE program by CAD-FEM coupling and be linked to

30 form an FE model which may be used for carrying out physical calculations.

The invention has the advantage that curve equations of first order are used for the transition between the

35 numerical and the analytic description of the object

data. As compared with reverse engineering that uses
curve equations of third or higher order, the complexity
of the equation system to be solved is reduced
considerably. Even if it is started out from a very fine
5   mesh to create an especially accurate three-dimensional
model of the object in question, the time saved by using
the less complex equation system is so large that the
overall calculation effort is reduced in spite of the
high accuracy of the model. Therefore, the invention
10   makes it possible to create an accurate three-dimensional
surface model, solid model or FE model of a tangible
existing object with relatively low calculation effort.

The invention may be embodied as a method as well as an
15   apparatus or a software product.

Concerning the apparatus, it should be noted that besides
a data processor for executing the data processing steps
of inputting the mesh model, breaking the mesh model into
20   bilinear surface elements, reuniting the bilinear surface
elements to a surface model or solid model, and '
optionally generating an FE model from the surface model
or solid model, there is provided a digitizer for
creating the mesh model of the object. Such a digitizer
25   includes all image forming devices such as cameras or X-
ray devices that form two-dimensional analogue or digital
images from which, in combination with image processing,
a three-dimensional mesh can be obtained. Such digitizers
also include optical and contact-type scanners which scan
30   the surface of the object to form a three-dimensional
point cloud from which, in combination with image
processing, a mesh is obtained. Here, it does not matter
whether the digitizer and the data processor are separate
or whether the digitizer uses the data processor for
35   executing image processing.

It goes without saying that the invention may be embodied
as a software product instead of an apparatus, with the
above-mentioned data processing being executed by
5   software routines when running on a computer. The
software product may be stored on a data carrier or it
may be directly loaded into the main storage of the
computer.

10   Further objects, advantages and features of the invention
can be gathered from the following detailed description
of embodiments and comparative examples under
consideration of the attached drawings. In the drawings:

15   Fig. 1 shows an image of a test person's face in form of
a point cloud, the image being digitized by optical
scanning;

Fig. 2 shows the point cloud of Fig. 1 after thinning
20   out;

Fig. 3 shows a mesh created from the point cloud of Fig.
2;

25   Fig. 4 shows a portion of the mesh shown in Fig. 3;

Figs. 5a to 5d illustrate a process of forming three
bilinear surface elements from three polygons of the
portion shown in Fig. 4 and uniting them;
30
Fig. 6 shows a surface model created from the mesh shown
in Fig. 3;

Fig. 7 shows an FE model of facial soft tissue created
35   from the surface model shown in Fig. 6;

Fig. 8 shows a digitized X-ray tomogram of a human skull
in the vicinity of the lower jaw, the skull boundaries
being marked and provided with points;

5

Fig. 9 shows, after homogenizing, a digital image of a
skull created from a plurality of tomograms and being in
form of a point cloud;

10   Fig. 10 shows a mesh created from the point cloud of Fig.
9;

Fig. 11 shows a solid model of the skull created from the
mesh shown in Fig. 10;

15

Fig. 12a shows a mesh model of a human ear and Fig. 12b a
model made of NURBS patches created from the mesh model
by reverse engineering;

20   Fig. 13 a conventional FE model of facial soft tissue
created by reconstruction;

Fig. 14 a conventional FE model of a tooth created by
point-based linking of layers;

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Fig. 15 a conventional FE model of a human skull created
by voxel-based linking of layers; and

Fig. 16 a conventional FE model of a lower jaw created by
30   linking a point cloud.

Referring to Figs. 1-7, a first embodiment of the
invention is described, explaining how a three-
dimensional surface model and a FE model of facial soft
35   tissue are created from a digitized image of a test

person's face.

A test person's face was digitized by means of a light-
coded triangulation method (TRICOLITE™ of the company
5   Steinbichler). For this purpose, a LCD projector threw a
series of stripe patterns on the face, which were
detected by two CCD cameras at different viewing angles.
The complete measurement took about two seconds. Using
geometrical analysis (triangulation principle), a three-
10 dimensional image of the facial surface was obtained in
form of a point cloud. Further details on the light-coded
triangulation method are disclosed in C. Holberg's
dissertation (citation in progress) "Erfassung von
Gesichtsoberflächen durch ein lichtkodiertes
15 Triangulationsverfahren", Ludwig-Maximilians-Universität
(LMU), Munich (2002).

Then, the point cloud obtained was filtered to get a
certain resolution and to safe on redundant data.
20 Specifically, those image points were erased whose
location hardly differed from those of the adjacent image
points, while those image points were retained whose
location differed from those of the adjacent image points
more clearly. As a result, the thinned-out point cloud
25 shown in Fig. 2 was obtained, in which the image points
are the closer the more the topology of the facial
surface changes.

Subsequently, the thinned-out point cloud was imported
30 into the image processing program RapidForm™ (INUS
Technology, Inc.) and linked to form a polygon mesh made
of triangular polygons. For obtaining a continuous clean
polygon mesh, the polygon mesh was freed from crossing,
redundant and non-manifold surfaces. In the present case,
35 the option of homogenizing the polygon mesh or increasing

or reducing the number of polygon surfaces was not used.
The result was the hole-free and cleaned polygon mesh
shown in Fig. 3, which was temporarily stored in DXF
format.

5

Subsequently, the polygon mesh stored in the DXF format
was imported into the program PolyTrans™ (Okino Computer
Graphics) to store the polygon mesh, without further
changes, in the neutral IGES format which enables data
10 exchange between different CAD, CAM and computer
visualizing systems. Owing to the export as an IGES file,
the polygon mesh was broken into bilinear NURBS patches
of entity #128. Then, the IGES file obtained was read
into the CAD program MechanicalDesktop™ (Autodesk Inc.)
15 where the image of the test person's face was henceforth
provided in form of individual surface elements (bilinear
NURBS patches) each corresponding to one polygon of the
previous polygon mesh. Using the function "Flächen
Zusammenheften" (i.e. "Surface Stitching"; other programs
20 use the term "Joining"), the individual surface elements
were united to form a surface composite, resulting in the
surface model of the test person's face shown in Fig. 6.
Subsequently, the surface model was exported by means of
the CAD-FEM interface AMACISOUT of the program in SAT
25 format to make the geometry of this surface model
accessible for CAD-FEM coupling.

Next, the individual processing steps are explained by
reference to Fig. 4 and Figs. 5a to 5d, which the image
30 data was subjected to at the time of breaking the polygon
mesh into the individual surface elements and uniting the
surface elements.

Fig. 4 shows a portion of the polygon mesh of Fig. 3
35 which is taken from an area of the test person's right

cheek. In this area, only the three thick polygons are
examined whose vertices or nodes are highlighted. These
three polygons are illustrated in Fig. 5a without
surroundings.

5

The polygons illustrated in Fig. 5a were converted into
the three bilinear NURBS patches shown in Fig. 5b by
converting them into the IGES format. As mentioned above,
NURBS patches are surface elements each defined by two

10 non-uniform rational B-splines, i.e. by two freeform
polynomial curves. Since the initial polygons were plane,
the pair of B-splines defining each surface element is
not curved either and is thus a curve of first order.
According to the invention, the NURBS patches are not

15 numerically described by the vertices of the respective
surface element anymore, but analytically by two curves
of first order or two straight lines. Since the initial
polygons were triangular, the resulting NURBS patches are
triangular as well. In other words, one of the end points

20 of one straight line of the NURBS patch coincides with
one of the end points of the other straight line with the
two straight lines forming two edges of the triangular
NURBS patch, while the third edge is obtained by
connecting the other end points of the straight lines.

25 Since each NURBS patch is defined by its own pair of
linear B-splines, each NURBS patch has its own edges
which are not shared with the adjacent surface elements.

As shown in Fig. 5c and Fig. 5d, the individual NURBS

30 patches were united with the adjacent NURBS patches by
using the stitching function. The stitching step performs
two tasks: First, this function stitches two or more
contiguous surfaces to create a surface composite.
Second, defects of geometry or topology are corrected,

35 which may occur during conversion due to different

internal tolerances and calculation errors. Thus, the
stitching step achieves a continuous surface composite
that can be used as a surface model.

5   The surface model of the test person's face shown in Fig.
6 was exported by means of the CAD-FEM interface and
imported into the FE program DesignSpace™ of Ansys, Inc.
The surface model was treated as a curved surface
structure complying with the rules of shell theory. After
10   assigning a uniform thickness, the structure was linked
to the three-dimensional FE model of facial soft tissue
shown in Fig. 7. Since the defect surfaces had already
been erased during cleaning of the polygon mesh, the
linking did not make difficulties, so that there were no
15   intersections or overlaps. The FE model had substantially
the same high resolution as the polygon mesh and the
surface model created in the CAD program. By determining
appropriate bearings and loads, this FE model made it
possible to calculate deformations, stresses and strains
20   in the facial soft tissue with high resolution. Such
calculations may be used for planning plastic surgery and
the like.

Next, a second embodiment is described by reference to
25   Figs. 8-11, explaining how a three-dimensional solid
model is created from digitized tomograms of a human
skull.

A set of forty-two digital X-ray tomograms was made of a
30   test person's skull by means of computed tomography.
Using the image processing program 3D-Dotor™ (Able
Software), the boundaries of the skull bone were
identified in the tomograms and the marked boundaries
were provided with several points. Fig. 8 shows an
35   example of such a tomogram in the vicinity of the lower

jaw bone, having boundaries and points.

The points marked in the individual tomograms were
combined to a three-dimensional point cloud, the
5 redundant data was removed by filters having a certain
resolution, and the remaining point cloud was
homogenized. The result was the thinned-out point cloud
shown in Fig. 9, in which the image points are the closer
the more the topology of the skull surface changes.
10

Subsequently, the thinned-out point cloud was linked to
form a polygon mesh consisting of triangular polygons,
and the polygon mesh was cleaned from intersecting,
redundant and non-manifold surfaces. Holes that may have
15 occurred were closed again. The resulting polygon mesh is
shown in Fig. 10.

Like in the first embodiment, the polygon mesh was
imported into the program PolyTrans™ (Okino Computer
20 Graphics) and broken into bilinear NURBS patches of
entity #128 to be subsequently stitched together under
correction of the errors in geometry or topology that had
occurred to form a surface composite. Since the polygon
mesh was already free from holes, the surface composite
25 had a continuous surface similar to that of a closed
solid, so that the stitching step automatically created a
solid model. The completed solid model is shown in Fig.
11 and had substantially the same resolution as the
initial polygon mesh, so that it was suitable for a high-
30 resolution FE model. The resulting FE model may be used
for simulating the effect of external forces on the
skull.

The above embodiments demonstrate that the invention
35 makes it possible to create highly accurate three-

dimensional models of tangible existing objects.

The following comparison of the invention with the
conventional reverse engineering method provides evidence
5   that the invention is also capable of reducing the
calculation effort.

For this purpose, it was started out from a mesh model of
the human ear consisting of 3386 triangular polygons. The
10 mesh is shown in Fig. 12a. On the one hand, the mesh was
converted as provided by the invention and, on the other
hand, it was converted by means of the reverse
engineering function of the program RapidForm™ (INUS
Technology, Inc.) into NURBS patches of IGES entity #128.
15 In both cases the 3386 polygons were converted into the
same number of NURBS patches. In case of the reverse
engineering, an additional model having a lower
resolution of 232 NURBS patches was prepared as shown in
Fig. 12b. The calculation time and the memory
20 requirements of the individual models can be gathered
from table 1.

<u>Table 1</u>

	Number of NURBS	Calculation time	Memory requirement (uncompressed)	Memory requirement (compressed)
Invention	3386	2,9 s	1,2 MB	0,4 MB
Reverse Engineering	3386	1983 s	29,6 MB	16,1 MB
Reverse Engineering	232	98 s	2,0 MB	1,1 MB

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Table 1 shows that the method according to the invention
requires considerably less calculation time and memory as
compared with the reverse engineering at the same

resolution (i.e. the same number of NURBS patches). If
the number of NURBS patches is reduced in reverse
engineering, the calculation time and the memory
requirement are reduced, but geometric inaccuracies have

5 to be put up with. The comparison between Figs. 12a and
12b shows that reverse engineering produces very smooth
surface transitions, but also amounts to a flawed
representation, in particular at the periphery of the
model (see the arrow in Fig. 12b). The inaccuracies at

10 the periphery are the more noticeable in reverse
engineering the more complex the structure to be
reproduced is and the lower the resolution (number of
NURBS patches produced) is. Similar flaws do not occur in
the invention.

15

Furthermore, it was found that, in particular when the
patch layout is automatically generated, the NURBS
patches created by reverse engineering result in
irregular, defect and twisted CAD surfaces that could not

20 be further processed (for example by means of CAD-FEM
coupling). Since the manual generation of patch layouts
is time-consuming, error-prone and can usually only be
accomplished by a skilled person, reverse engineering is
not a practical solution for creating FE models from

25 digitized anatomical structures such as the ear shown in
Fig. 12a.

It follows that the invention is not only capable of
providing a highly accurate time-saving and memory-saving

30 alternative for reverse engineering, but develops new
applications in the field of modeling highly complex
objects such as in the field of biotechnology, which were
not accessible up to date for reverse engineering or
other conventional methods.

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